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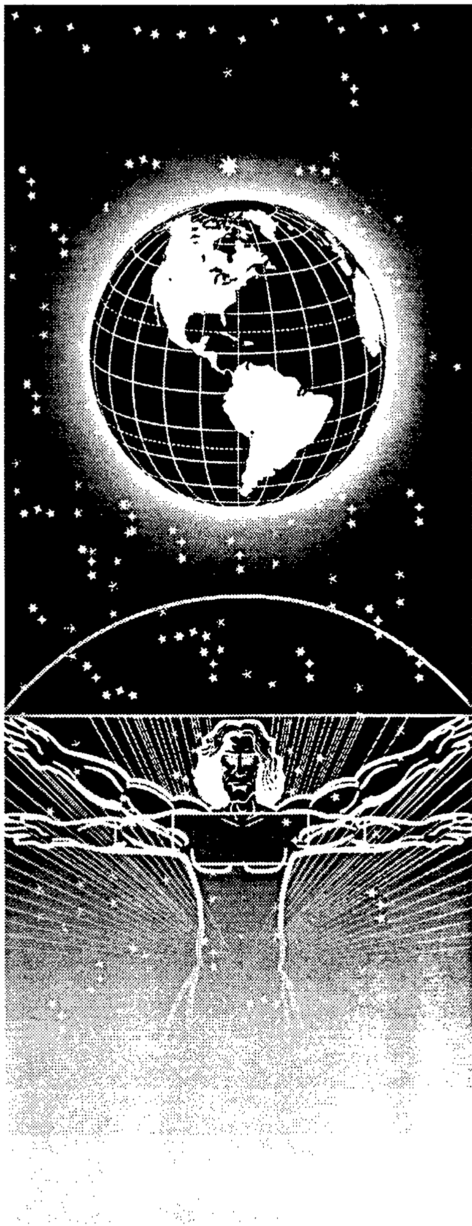

UNITED STATES AIR FORCE RESEARCH LABORATORY

EFFECTS OF LOCALIZED AUDITORY INFORMATION ON VISUAL TARGET DETECTION PERFORMANCE USING A HELMET-MOUNTED DISPLAY

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An experiment was conducted to evaluate the effects of localized auditory information on visual target detection performance. Visual targets were presented on either a wide field-of-view dome display or a helmet-mounted display and were accompanied by either localized, nonlocalized, or no auditory information. The addition of localized auditory information resulted in significant increases in target detection performance and significant reductions in workload ratings as compared with conditions in which auditory information was either nonlocalized or absent. Qualitative and quantitative analyses of participants' head motions revealed that the addition of localized auditory information resulted in extremely efficient and consistent search strategies. Implications for the development and design of multisensory virtual environments are discussed. Actual or potential applications of this research include the use of spatial auditory displays to augment visual information presented in helmet-mounted displays, thereby leading to increases in performance efficiency, reductions in physical and mental workload, and enhanced spatial awareness of objects in the environment.

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Effects of Localized Auditory Information on Visual Target Detection Performance Using a Helmet-Mounted Display

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An experiment was conducted to evaluate the effects of localized auditory information on visual target detection performance. Visual targets were presented on either a wide field-of-view dome display or a helmet-mounted display and were accompanied by either localized, nonlocalized, or no auditory information. The addition of localized auditory information resulted in significant increases in target detection performance and significant reductions in workload ratings as compared with conditions in which auditory information was either nonlocalized or absent. Qualitative and quantitative analyses of participants' head motions revealed that the addition of localized auditory information resulted in extremely efficient and consistent search strategies. Implications for the development and design of multisensory virtual environments are discussed. Actual or potential applications of this research include the use of spatial auditory displays to augment visual information presented in helmet-mounted displays, thereby leading to increases in performance efficiency, reductions in physical and mental workload, and enhanced spatial awareness of objects in the environment.

INTRODUCTION

Researchers (Furness, 1986; Stinnett, 1989) have recognized the tremendous potential that helmet-mounted displays (HMDs) and other virtual environment (VE) technologies have for enhancing pilot effectiveness in future air combat environments. However, in spite of the potential benefits, HMDs continue to be challenged by several technological limitations, including narrow fields of view (FOV), excessive helmet weight and bulkiness, display lag, inaccuracies in head position and tracking technologies, and suboptimal display resolution (see Beal & Sweetman, 1994, for review). Indeed, such limitations may potentially disrupt the highly coordinated perceptual-motor skills required to pilot modern tactical aircraft, thereby jeopardizing performance efficiency and pilot safety. Accordingly, we believe it is imperative to conduct empirical evaluations of HMDs and other virtual environment technologies so as to determine their effects on human perception and performance.

Along these lines, Hettinger, Nelson, and Haas (1996) compared visual target detection in an HMD with that in a conventional dome display. In terms of performance efficiency, the HMD was found to be significantly poorer than the dome display with regard to percentage of correct detections (HMD = 73.4%, dome display = 99.8%) and the amount of time required to make a correct detection (HMD = 49.5 s, dome display = 39.4 s). In addition, participants' ratings of workload and fatigue were significantly higher in the HMD than in the conventional dome display.

One potential way to offset the problems reported by Hettinger et al. (1996) would be to provide operators with synthetic or virtual

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three-dimensional (3D) auditory information, thereby exploiting the human auditory system's ability to direct the attention of the operator to the spatial location of the target. Indeed, numerous investigators (Barfield, Cohen, & Rosenberg, 1997; Begault & Pittman, 1996; Bronkhorst, Veltman, & Breda, 1996; McKinley, Ericson, & D'Angelo, 1994; Perrott, Cisneros, McKinley, & D'Angelo, 1996; Perrott, Sadralodabai, & Saberi, 1991; Sorkin, Wightman, Kistler, & Elvers, 1989; Wenzel, 1992; Wightman & Kistler, 1989) have recognized the potential of spatialized auditory displays for directing one's attention and enhancing spatial awareness. Accordingly, spatially localized auditory interfaces may be particularly well suited for tasks that require pilots to locate objects (e.g., targets, threats, waypoints, etc.) using narrow FOV HMDs.

Toward that end, the present investigation was designed to evaluate the effects of virtual localized auditory information on target detection performance and workload when using an HMD.

METHOD

Participants. The 10 participants (3 women and 7 men) were naive to the purpose of the experiment. Their ages ranged from 19 to 25 years with a mean of 21.5 years. A preexperimental screening for visual and auditory acuity ensured that all participants had 20/20 or corrected-to-20/20 binocular visual acuity and normal auditory functioning. Participants were paid $5/h for their participation.

Experimental design. There were four visual conditions in the experiment: full FOV, mechanically limited (ML) FOV, software-limited (SL) FOV, and HMD. In addition, there were four auditory conditions: no auditory information (none), nonlocalized auditory information (NL), auditory information localized in azimuth and elevation (two-dimensional [2D]), and auditory information localized in azimuth, elevation, and range (3D). The visual conditions were combined factorially with the auditory conditions to provide 16 experimental conditions. Participants completed each combination of the 16 possible auditory and visual conditions with the constraint that a single visual condition was paired with all four auditory conditions during each experimental session.

Apparatus. An SGI Onyx RealityEngine2 was used to generate the visual stimuli in all experimental conditions, collect performance and head position data, and synchronize all external devices. Visual targets consisted of light green monochrome silhouettes of SU-27 aircraft presented on a dark monochrome background.

The full visual condition featured the 150° horizontal (H) × 70° vertical (V) FOV of the Armstrong Laboratory's Synthesized Immersion Research Environment (SIRE) dome display. In all of the other visual conditions, participants were provided with a 60° H × 40° V FOV. In the mechanically limited (ML) condition, a transparent visor that restricted participants' FOV was attached to the flight helmet. Similarly, the software-limited (SL) condition featured a software-generated, head-slaved viewing "window" that restricted participants' FOV on the spherical dome display surface. Finally, the HMD was configured to provide a similar 60° H × 40° V FOV.

Auditory warning tones – pulsed pink noises with a cutoff frequency of 11 kHz – were presented binaurally to participants via a set of Sennheiser HD 250 II Studio Monitor headphones. The none auditory condition served as a control condition; hence, no auditory warning tone was presented in this condition. In the NL auditory condition, an acoustic warning tone accompanied the appearance of the visual target but provided no information regarding the spatial location of the target. In the localized auditory conditions (2D and 3D), the warning tone was generated to be perceived as an externalized signal so that its spatial location corresponded to that of the visual target. The 2D warning tone included azimuth and elevation cues, whereas the 3D tones included azimuth, elevation, and distance cues.

Virtual auditory localization. The Armstrong Laboratory's Auditory Localization Cue Synthesizer and the Convolvotron™ 3D audio reference system (see McKinley et al., 1994, and Wenzel, 1992, for descriptions) were used to localize auditory warning tones. Both devices are high-speed digital audio signal processing systems that deliver real-time, 3D

sound over conventional headphones. In this experiment, nonindividualized head-related transfer functions were used to generate localization cues. Head position and orientation were determined with an Ascension Technology Flock of Birds™ tracker.

HMD. A Kaiser Electronics SimEye 2500 helmet-mounted display was used in the HMD condition. The helmet consists of two green phosphor monochrome CRTs and has a nominal resolution of 1280 H × 1024 V pixels. The field of regard in the HMD was configured to match that of the SIRE dome display, approximately 150° H × 70° V. Given that the SimEye 2500 weighs approximately four pounds (1.81 kg), participants were required to wear a flight helmet (matched for weight) in all of the other visual conditions in order to control for differences in performance and workload attributable to this factor.

Dome display. A Seos Displays Ltd. Prodas S600HB dome-display system was used in all visual conditions except the HMD condition. It consists of six 1280 H × 1024 V pixels resolution cathode ray tube projectors arranged in two rows of three projectors.

Procedure. Prior to testing, participants were given detailed instructions specific to the particular visual or auditory condition on which they would be tested. The experimenter explained that on each trial a single target would approach from a random position on the dome (or HMD) and that the participant's task was to visually scan the display surface and detect the visual target as quickly as possible. All target aircraft approached from beyond visual range along a straight-on trajectory at a constant velocity. Participants performed 12 practice trials followed by 14 experimental trials (12 experimental trials and 2 catch trials) for each combination of the 16 possible auditory and visual conditions. Catch trials were those in which no visual targets were presented and were included in order to discourage premature responses.

Participants pressed a mouse button as soon as they were able to visually detect the approaching target. When this occurred, the dome (or HMD) display was blanked and participants marked the location of the target with a head-slaved cursor that appeared on the display. Participants received feedback after completing each block of 14 trials and rated the perceived mental workload associated with that block of trials by completing the NASA Task Load Index. An experimental session ended after all four auditory conditions had been completed within a single visual condition. Testing continued in following sessions with a different visual condition matched with all four auditory conditions.

RESULTS

Target Detection Efficiency

Percentage of correct detections. Mean percentages of correct detections for all experimental conditions were analyzed with a 4 (visual conditions) × 4 (auditory conditions) repeated-measures analysis of variance (ANOVA), which revealed that the main effects for the visual and auditory factors and the Visual × Auditory interaction were statistically significant, $F(3, 27) = 38.17$, $p < .05$, $F(3, 27) = 82.75$, $p < .05$, and $F(9, 81) = 9.49$, $p < .05$, respectively. The Visual × Auditory interaction is illustrated in Figure 1, in which mean percentages of correct detections are plotted for the four visual conditions under each of the auditory conditions.

The interaction was further investigated by tests of the simple main effects of auditory conditions within each level of the visual conditions and visual conditions within each level of the auditory conditions. All simple main effects were statistically significant ($p < .05$) with the exception of two tests: the effect for visual conditions within the 3D auditory condition, $F < 1$, and the effect of auditory condition within the full visual condition, $F(3, 27) = 2.92$, $p > .05$. The former implies that the 3D auditory condition served to equate target detection performance in all four visual conditions, whereas the latter attests to the advantage of providing operators with a wide FOV when performing visual target detection tasks.

Distance of correct detections. The mean distances at which targets were correctly detected, illustrated in Figure 2, were used as an additional index of target detection efficiency. These data were analyzed with a similar repeated-measures ANOVA, which indicated

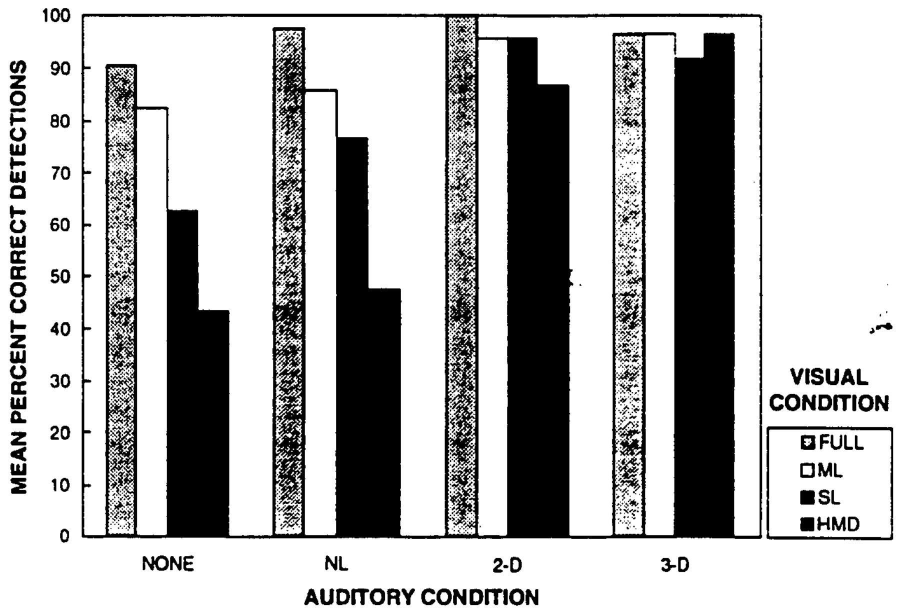

Figure 1. Percentage of correct detections under all experimental conditions. Adding localized auditory information (i.e., 2D and 3D conditions) increased detection scores across all visual conditions. This effect was especially dramatic in the case of the HMD condition, for which detection scores in the localized auditory conditions were approximately 45% higher than those associated with conditions in which auditory cues were either nonlocalized or absent.

that the visual and auditory main effects were statistically significant, $F(3, 27) = 13.82$, $p < .05$, and $F(3, 27) = 29.61$, $p < .05$, respectively. In addition, the Visual × Auditory interaction was found to be statistically significant, $F(9, 81) = 2.38$, $p < .05$. Further investigation of the interaction revealed that all tests of the simple main effects were statistically significant ($p < .05$) with the exception of the effect of visual conditions within the 2D auditory condition, $F(3, 27) = 2.11$, $p > .05$. This nonsignificant effect is important in that it implies that performance efficiency in the four visual conditions was equivalent when 2D localized auditory information was presented.

Workload Ratings

Overall workload. Mean overall workload scores on the NASA Task Load Index are displayed in Table 1 for all experimental conditions. An ANOVA of these data revealed significant main effects for the visual conditions, $F(3, 27) = 9.58$, $p < .05$, and auditory conditions, $F(3, 27) = 45.70$, $p < .05$, but failed to reveal a significant Visual × Auditory interaction ($p > .05$). Post hoc pairwise comparisons (t tests with Bonferroni-adjusted alpha levels) revealed that workload scores associated with the 2D and 3D conditions were both significantly lower ($p < .0083$) than with the none and NL conditions. In addition,

TABLE 1: Mean Overall Workload Ratings (NASA-TLX) for All Experimental Conditions

Visual Conditions	Auditory Condition				
	None	NL	2D	3D	Mean
Full	63.43	63.73	52.23	56.40	58.95
ML	70.47	59.37	47.47	53.10	57.60
SL	69.93	66.36	50.53	55.30	60.53
HMD	75.03	79.23	68.10	65.07	71.86
Mean	69.72	67.17	54.58	57.47	

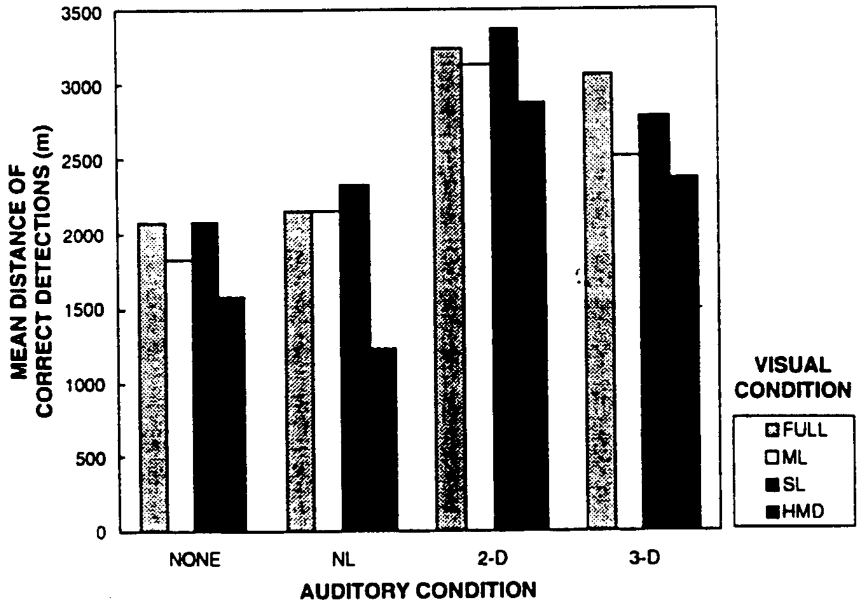

Figure 2. Mean distance of correct detection under all experimental conditions. The localized auditory conditions (*M* 2D = 3165 m and *M* 3D = 2697 m) were associated with higher target detection efficiency as compared with the nonlocalized conditions (*M* none = 1894 m and *M* NL = 1973 m). As was the case with percentage correct detections, the effects of adding localized auditory cues were greatest in the HMD condition; localized auditory information effectively doubled the distance at which targets were correctly detected in the HMD.

no significant differences ($p > .0083$) in workload ratings were revealed between the 2D and 3D conditions or the none and NL conditions. Finally, post hoc pairwise comparisons confirmed that workload ratings associated with the HMD conditions were significantly greater ($p < .0083$) than all other visual conditions and that the full, ML, and SL conditions were not significantly different from one another.

Analysis of Head Position Data

Qualitative and quantitative analyses. Head position data were used to create plots of participants' head motion activity during each trial and to calculate two quantitative metrics of head motion: total angular head displacement (i.e., angular distance that the head traveled throughout an experimental trial) and average head velocity. Figures 3a through 3d depict typical head motions during target search and show differences in search strategies in the full visual condition among each of the four auditory conditions (none, NL, 2D, and 3D, respectively).

Angular head displacement. Angular head displacement data were subjected to a 4 (visual conditions) × 4 (auditory conditions) repeated-measures ANOVA, which revealed significant main effects for the visual and auditory factors, $F(3, 27) = 14.35$, $p < .05$, and $F(3, 27) = 50.13$, $p < .05$, respectively, and a significant Visual × Auditory interaction, $F(9, 81) = 1.98$, $p < .05$. The Visual × Auditory interaction is presented in Figure 4, in which mean angular head displacement is plotted under all experimental conditions. Further exploration of the Visual × Auditory interaction with tests of the simple main effects indicated that all tests were statistically significant ($p < .05$) except for the effect of visual conditions within the 3D auditory condition, $F(3, 27) = 2.83$, $p > .05$.

Average head velocity. Mean head velocities for all experimental conditions, which are presented in Table 2, were analyzed with a similar 4 (visual conditions) × 4 (auditory conditions) repeated-measures ANOVA. The main effects for visual conditions, $F(3, 27) = 8.67$, $p < .05$, and auditory conditions, $F(3,$

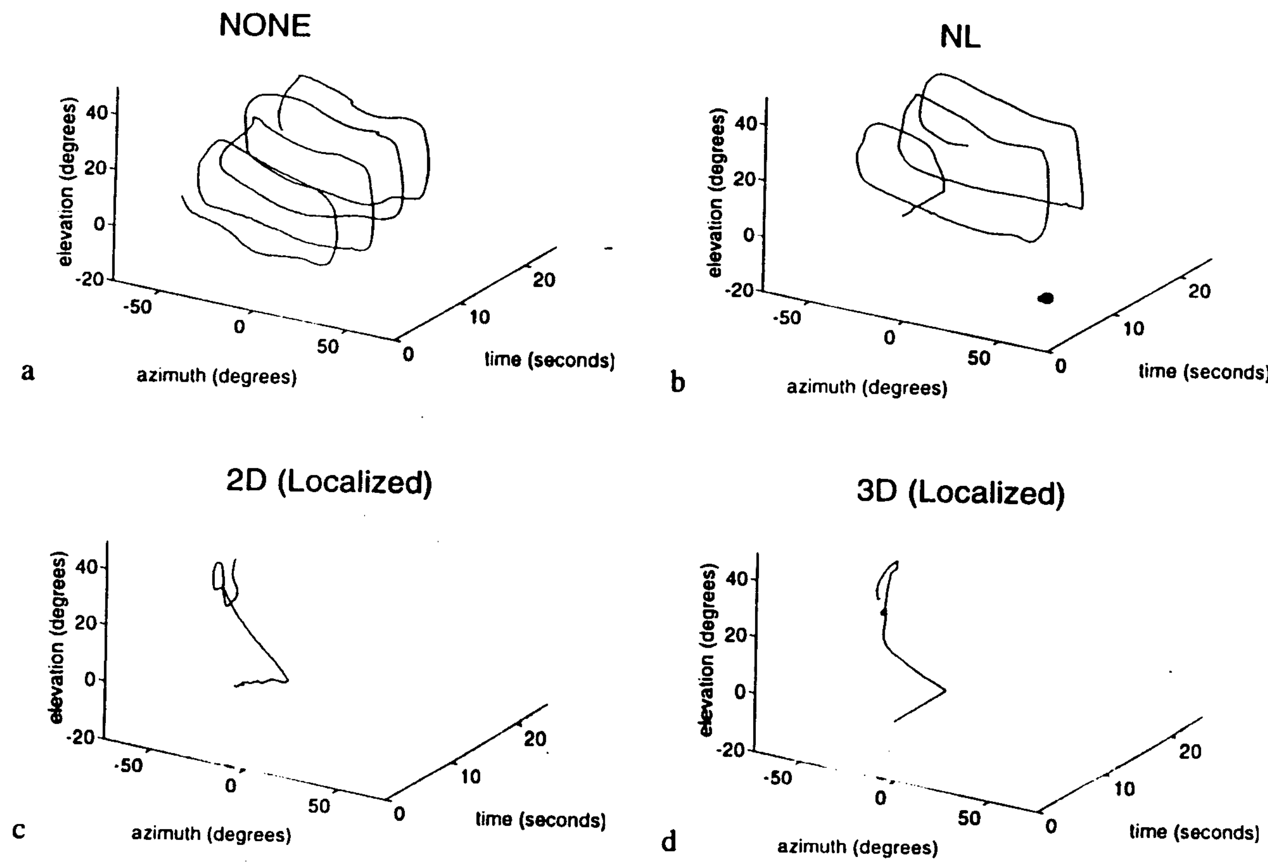

Figure 3. Time history plots of participants' head motions or search strategies for the full field-of-view visual condition under each auditory condition. Panels a and b show that search strategies in the nonlocalized auditory conditions were similar and involved a "circular" search of the entire field of regard. In addition, close inspection of panel b (the NL auditory condition) indicates that head motion activity was delayed until the nonlocalized warning tone was provided. In contrast, panels c and d show that the addition of localized auditory information gave rise to a qualitatively different type of search strategy. Rather than encompassing the entire field of regard, target search in the 2D and 3D conditions was very directed.

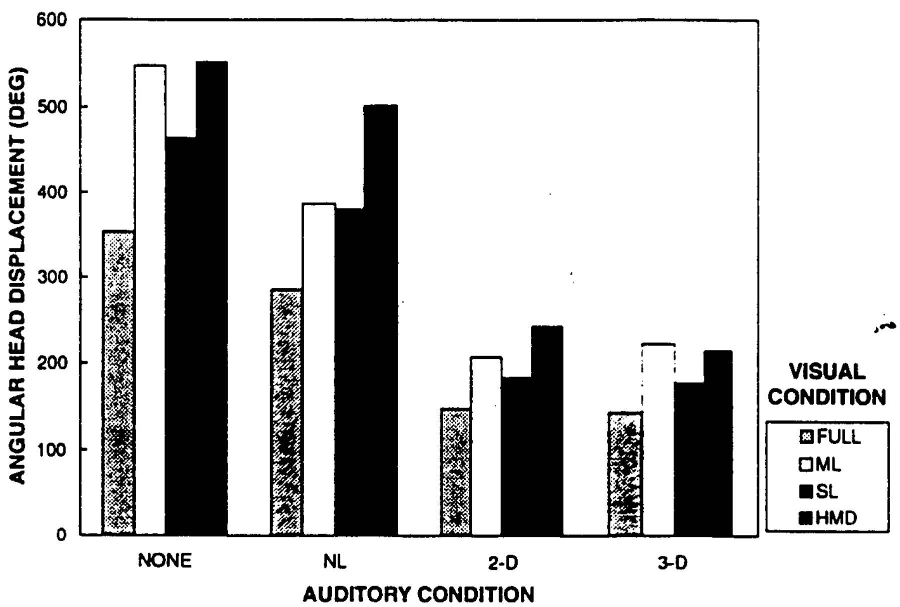

Figure 4. Mean average head velocity under all experimental conditions. Angular head displacements associated with the 2D (M = 195.55°) and 3D (M = 190.03°) conditions were substantially lower than those with the none (M = 478.56°) and NL (M = 388.46°) auditory conditions. In addition, angular head displacement was generally greater in the limited field-of-view conditions (M ML = 340.93°, M SL = 301.17°, M HMD = 378.01°) than with the full (M = 232.48°) condition, especially in conjunction with the none and NL conditions.

27) = 41.15, $p < .05$, were found to be statistically significant; however, the Visual × Auditory interaction lacked statistical significance ($p > .05$). Inspection of Table 2 indicates that velocities in the none and NL conditions were approximately two times greater than those associated with the 2D and 3D auditory conditions. Post hoc pairwise comparisons (t tests with Bonferroni-adjusted alpha levels) of the four auditory conditions revealed that all comparisons were statistically significant ($p < .0083$) with the exception of the comparison between the 2D and 3D auditory conditions. Pairwise comparisons of the four visual conditions revealed that only the comparison between the full and HMD conditions reached significance, $t(9) = 3.79$, $p < .0083$.

DISCUSSION

The results of this experiment demonstrate the beneficial effects of virtual localized auditory information on performance and perceived workload in a visual target detection task. All metrics of performance efficiency, workload, and head motion revealed a significant advantage for conditions in which localized auditory cues were provided. Collectively, these outcomes support the position that

TABLE 2: Mean Head Velocities (°/s) across All Experimental Conditions

	Auditory Conditions				
Visual Conditions	None	NL	2D	3D	Mean
Full	42.79	34.10	20.00	18.98	28.97
ML	62.55	45.37	27.58	26.66	40.54
SL	52.74	44.41	24.42	22.59	36.04
HMD	58.19	52.31	30.18	26.34	41.75
Mean	54.07	44.05	25.54	23.64	

localized auditory information may be effective in alleviating the deleterious effects associated with performing a target detection task using an HMD.

What relevance do the present results have for application domains in which HMDs will be used? First, in the absence of localized auditory cues, all metrics of target detection performance, workload, and head motion activity associated with the HMD were far inferior to those achieved in the full FOV visual condition. In this regard, the present results corroborate and extend the findings reported by Hettinger et al. (1996). Consequently, if HMDs are used to support tasks that involve accurate and rapid target detection, some type of additional display is needed to compensate for these effects.

Second, a particularly striking outcome that emerges from the present investigation is that virtual localized auditory information was effective in mitigating the negative effects associated with performing a visual target detection task with an HMD. In fact, the addition of localized auditory information served to equate the HMD with the other viewing conditions in terms of percentage correct detections (see Figure 1), distance at which targets were correctly detected (see Figure 2), and average angular head displacement (see Figure 4). Accordingly, we view these data as strong preliminary support for the inclusion of virtual localized auditory cueing systems in HMDs, especially when operators are required to monitor and detect objects located outside of their FOV. However, we also recognize that our findings may not generalize to more-complex visual detection tasks in HMDs. Along these lines, we recommend that future investigations be conducted to assess the effects of virtual localized auditory cues on visual detection tasks that involve multiple targets, visual distractors, and nonstationary targets.

Last, in addition to enhancing target detection performance in the HMD condition, localized auditory cues were associated with less overall head motion and reductions in average head velocity. This finding is especially pertinent to tactical airborne applications, given the additional weight and offset center of gravity associated with HMDs and the fact that tactical aircraft often operate in elevated or high g. Namely, reduction in the amount of head motion required to detect targets in high-g environments is anticipated to reduce the risk of neck and shoulder fatigue, pilot workload, and neck strain and injury.

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REFERENCES

Barfield, W., Cohen, M., & Rosenberg, C. (1997). Visual and auditory localization as a function of azimuth and elevation. *International Journal of Aviation Psychology, 7*, 123–138.

Beal, C., & Sweetman, B. (1994). Helmet-mounted displays: Are we jumping the gun? *International Defense Review, 9*, 69–75.

Begault, D. R., & Pittman, M. T. (1996). Three-dimensional audio versus head-down traffic alert and collision avoidance system displays. *International Journal of Aviation Psychology, 6*, 79–93.

Bronkhorst, A. W., Veltman, J. A. H., & Breda, L., van. (1996). Application of a three-dimensional auditory display in a flight task. *Human Factors, 38*, 23–33.

Furness, T. A. (1986). The super cockpit and its human factors challenges. In *Proceedings of the Human Factors Society 30th Annual Meeting* (pp. 48–52). Santa Monica, CA: Human Factors and Ergonomics Society.

Hettinger, L. J., Nelson, W. T., & Haas, M. W. (1996). Target detection performance in helmet-mounted and conventional dome displays. *International Journal of Aviation Psychology, 6*, 321–334.

McKinley, R. L., Ericson, M. A., & D'Angelo, W. R. (1994, May). Three-dimensional auditory displays: Development, applications, and performance. *Aviation, Space, and Environmental Medicine, 65*, 31–38.

Perrott, D. R., Cisneros, J., McKinley, R. L., & D'Angelo, W. R. (1996). Aurally aided visual search under virtual and free field listening conditions. *Human Factors, 38*, 702–715.

Perrott, D. R., Sadralodabai, T., & Saberi, K. (1991). Aurally aided visual search in the central visual field: Effects of visual load and visual enhancement of the target. *Human Factors, 33*, 389–400.

Sorkin, R. D., Wightman, F. L., Kistler, D. S., & Elvers, G. C. (1989). An exploratory study of the use of movement-correlated cues in an auditory head-up display. *Human Factors, 31*, 161–166.

Stinnett, T. A. (1989). Human factors in the super cockpit. In R. Jensen (Ed.), *Aviation psychology* (pp. 1–37). Brookfield, VT: Gower Publishing.

Wenzel, E. M. (1992). Localization in virtual acoustic displays. *Presence, 1*, 80–106.

Wightman, F. L., & Kistler, D. J. (1989). Headphone simulation of free-field listening: II. Psychophysical validation. *Journal of the Acoustical Society of America, 82*, 868–878.

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